A 1.8 mJ, picosecond Nd:YVO_4 bounce amplifier pump front-end system for high-accuracy XUV-frequency comb spectroscopy

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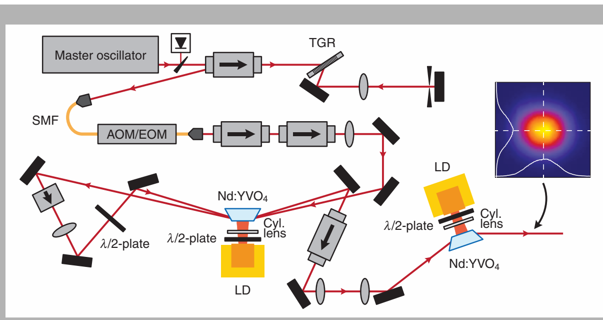
Abstract: We present an 880 nm quasi-continuously pumped, grazing-incidence "bounce" amplifier system, capable of producing picosecond pulses (12 – 100 ps) and tailored pulse sequences at the mJ-level. More than 1.8 mJ of pulse energy was achieved for a 58 ps pulse, using sub-100 pJ seeding energy (up to a repetition rate of 300 Hz). Owing to saturation effects, the pulse-to-pulse energy fluctuations were as low as 0.3% rms. The time delay between these pulses can be changed between 8 ns and >1 μs, providing a promising pump laser system for parametric amplification and subsequent upconversion of near-infrared frequency combs to the extreme ultraviolet (XUV).



Schematic of the pump-frontend system

A 1.8 mJ, picosecond Nd:YVO$_4$ bounce amplifier pump front-end system for high-accuracy XUV-frequency comb spectroscopy

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Key words: diode-pumping; ultra-high gain amplifier; Nd:YVO$_4$; frequency comb spectroscopy

1. Introduction

A variety of industrial and scientific applications require high peak power (megawatts to gigawatts), picosecond pulses, ranging from applications such as material processing [1] to driving optical parametric chirped pulse amplifiers (OPCPA [2]). Previously we have shown that such a high-power OPCPA system can also be used to amplify and subsequently up-convert selected pulses from a near-infrared frequency comb (FC), while conserving the phase coherence of the FC seed pulses [3]. By using two up-converted pulses and scanning their relative delay on a sub-fs-scale, Ramsey-like signals were obtained and XUV-FC spectroscopy at the MHz-level has been demonstrated [4]. The technical challenge for the amplifier system is to produce two equal pump pulses, synchronized to (multiples of) the cavity round-trip time of the FC seed pulses. In the previous system this was achieved by amplifying a single pulse with a Nd:YAG regenerative-amplifier to the mJ-level and subsequent splitting and recombining with an optical delay line. A non-saturated Nd:YAG post-amplifier then increased the pulse energy to the 100 mJ-level required for pumping of the OPCPA. From a technical point of view, the optical delay line limited the delay between the pulse pairs to tens of nanoseconds and therefore the achievable accuracy with the Ramsey-like signals [12]. Much longer delays >1 μs can be realized by employing amplifiers providing high single-pass gain and therefore allowing compact geometries with short optical path-lengths in the amplifier. In that case pulses can be picked and amplified directly from the master oscillator, without interfering with each other during the amplification process.

One way of achieving ultra-high single pass gain are grazing-incidence "bounce" amplifiers, made of highly absorbing Nd^{3+}-doped gain media [5]. Bounce amplifiers

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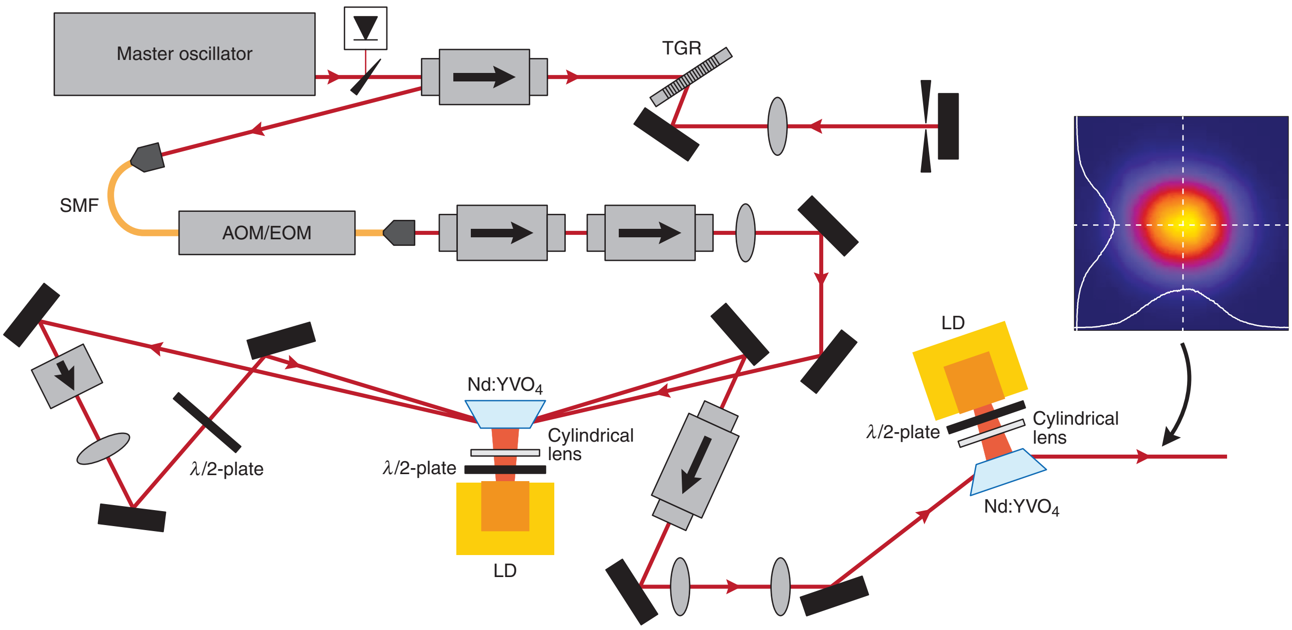

Figure 1 (online color at www.lasphys.com) Schematic of the experimental setup illustrating spectral selection (TGR – transmission grating), temporal selection (SMF – single-mode fiber, AOM – acousto-optical modulator, EOM – electro-optical modulator), and the QCW-pumped Nd:YVO_4 amplifier (LD – laser diode). The inset shows the amplified beam profile

have been employed in a variety of configurations (see e.g. [5–9]). By using high peak power, quasi-continuous wave (QCW) pump diodes, pulse energies up to 1 mJ have been reported for sub-nanosecond pulses with microjoule seeding energies [9, 10].

Previously we demonstrated the combination of a single bounce amplifier with a programmable pulse-picking unit, capable of producing tailored pulse sequences at the 100 μJ level [11]. In this letter we report on the extended version of that amplifier system, capable of delivering more than 1.8 mJ in 58 ps pulses using sub-100 pJ seeding energy. To the best of our knowledge, this presents both the highest gain and highest pulse energy that have been reported for amplifiers in a single-bounce geometry. With the help of spectral clipping and high-contrast modulators, the system supports pulse durations in the range of 12 to 100 ps and produces highly stable (0.3% rms), high-contrast millijoule pulse sequences. This energy level is sufficient for seeding our previously used flashlamp-pumped post-amplifier resulting in 140 mJ of pulse energy at 1064 nm.

2. Experimental setup

2.1. Master oscillator

A simplified sketch of the experimental setup is shown in Fig. 1. The master oscillator is a home-build Nd:YVO_4 laser, pumped with 25 W at 880 nm and passively mode-locked with a semiconductor saturable absorber mirror. It provides Gaussian-shaped pulses of 0.25 nm spectral bandwidth in a 126 MHz pulse train with 5 W average output power. In the OPCPA system, pump and seed pulses have to be synchronized on a sub-picosecond scale to avoid intensity jitter. Therefore the repetition rate of the oscillator is locked to a stable reference frequency *via* a piezo-mounted mirror; slow thermal drifts were compensated *via* feed-back on the oscillator baseplate temperature.

2.2. Spectral clipping and pulse picking

Typical pump pulse durations required for our high power optical parametric amplifier are in the order of a few tens of picoseconds. Therefore the initial pulse duration of 12 ps was adjusted by spectral clipping *via* a movable slit close to the Fourier plane of a 4f-grating-system. The high-energy pulses from the master oscillator (40 nJ) enable a considerable flexibility in terms of the amplified bandwidth and center wavelength, leaving sufficient pulse energy for subsequent amplification in the saturated regime. The system supports Gaussian-shaped pulses from 12 ps to about 100 ps (10 pJ seeding energy for the first amplifier). For the reported experiments, the seed pulse duration was adjusted to $\sim$60 ps (Fig. 2a – Fig. 2d), according to the requirement of our amplifier system [4]. The center wavelength was matched to the peak wavelength of the ampli-

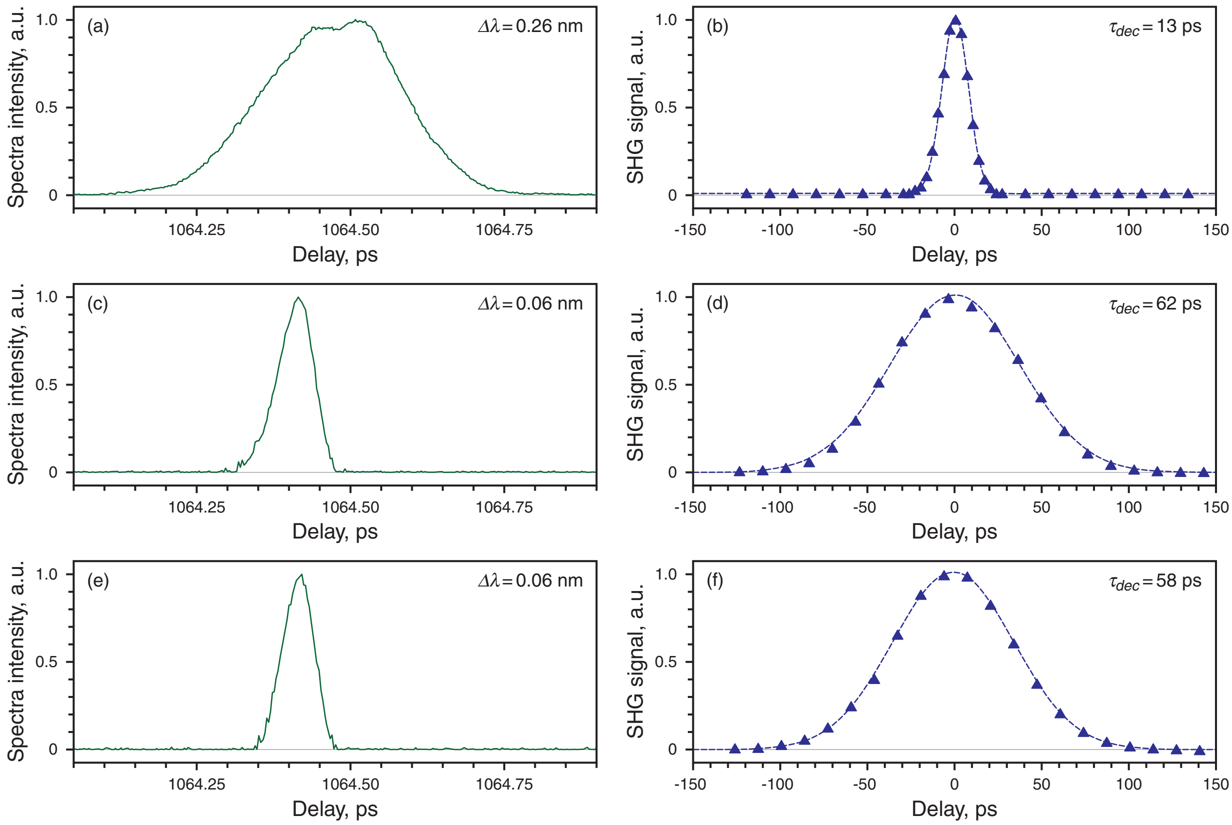

Figure 2 (online color at www.lasphys.com) Optical spectra (left column) and second harmonic, background-free autocorrelations (right column, τ_{dec} is the deconvolved pulse duration derived from the Gaussian fits, indicated by the dashed lines) of the full bounce amplifier bandwidth (a, b), the clipped seeding pulse (c, d), and the amplified pulse (e, f)

fied spontaneous emission (ASE) spectrum of the amplifier for maximum gain.

The full pulse train was then coupled into a single-mode fiber in order to spatially filter the beam and mechanically decouple the oscillator from the amplifier. In addition, it allowed the implementation of a fast and programmable fiber-coupled pulse-picking system, which is described in detail in [11].

2.3. Grazing incidence amplifier

After spectral and temporal selection the pulse train passes a double, >80 dB isolation stage to prevent back reflections into the pulse-picking system. The pulses of sub-100 pJ energy were then amplified in a bounce amplifier system comprising of two Nd:YVO_4 crystals, both 5° wedged and anti-reflection coated for pump and lasing wavelength. Among the range of Nd^{3+}-doped gain materials, Nd:YVO_4 was chosen as gain material because of its large stimulated emission cross section ($\geq 1.1\times10^{-18}$ cm^2 [14]) and the good spectral overlap with the emission spectrum of Nd:YAG, which is still commonly used for high energy post-amplification because of its superior thermal properties. The first crystal ($2\times4\times20$ mm^3, 1 at.%-doped) was pumped with 135 μs long pulses from a 180 W peak-power QCW 880 nm linear diode array. The pump pulse duration was not increased any further to limit excess ASE in the first amplifier stage, which otherwise extracts a considerable part of the stored energy in the following amplifier sections.

In addition, a second, $4\times6\times20$ mm^3 crystal was implemented and pumped by a similar diode, but with 200 μs long pulses of 250 W peak-power. In order to increase the damage threshold for the pump light, a lower doping of 0.5 at.% was chosen for the second crystal [13]. In both cases, half-waveplates were used to rotate the polarization of the pump beam to be parallel to the c-axis of the crystal, and cylindrical lenses were used to adjust the beam height to about 0.6 mm (the first crystal) and 0.9 mm (the second crystal). The maximum repetition rate of the pump pulses for this experiment was 300 Hz due to the available diode driver, but is in principle only limited by the maximum duty cycle of the QCW diodes of 10%.

The first crystal was double-passed by the seed beam with diameters and internal grazing angles of 0.3 mm and

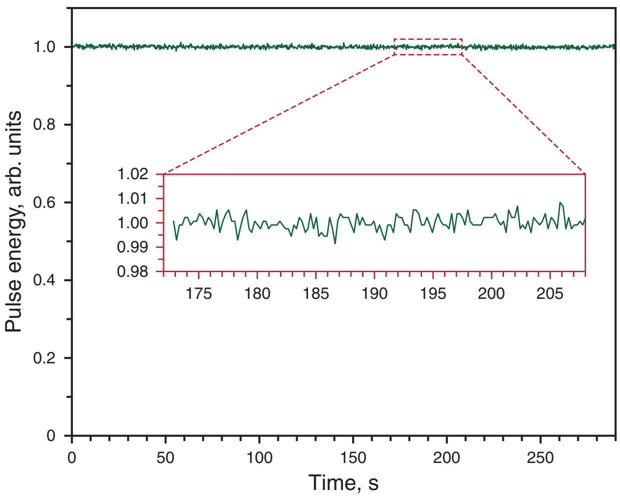

Figure 3 (online color at www.lasphys.com) Measured pulse energy after the bounce amplifier in single-pulse operation (0.3% rms)

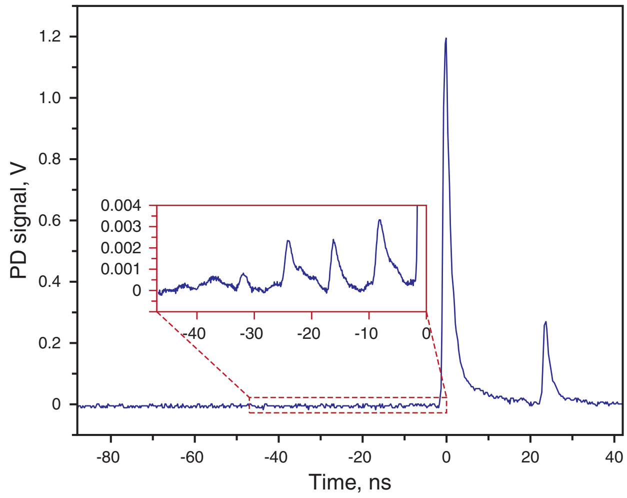

Figure 4 (online color at www.lasphys.com) Time trace of an amplified pulse pair of equal seeding energy (24 ns spacing). The pulse energy of the second pulse is decreased by a factor four due to gain depletion. The inset shows the amplified short time contrast of >400:1

2.8° (the first pass), and 0.4 mm and 3.4° (the second pass); the triangular-shaped delay arm allowed the incorporation of a low-power, 30 dB isolator. After double-passing the first crystal, the seed beam diameter was increased to 0.9 mm and sent through the second amplifier crystal at an internal grazing angle of 4.5°. Apart from suppressing dangerous back-reflections of the amplified seed beam, the two isolators in between the amplifier stages also prevent backwards seeding of the individual stages, which otherwise significantly reduces the available stored energies in the crystals.

3. Results and discussion

3.1. Single pulse operation

At a repetition rate of 300 Hz, we obtained 1.83 mJ of pulse energy using 62 pJ seeding energy. To the best of our knowledge, this is the highest net-gain (75 dB) and pulse energy achieved so far for this amplifier geometry. As can be seen in Fig. 2e and Fig. 2f, spectrum and pulse duration remain basically unchanged during the amplification process, indicating the absence of significant nonlinear effects and gain-narrowing. Decreasing the repetition rate by a factor of ten revealed no apparent change of the amplified beam profile, hence no deterioration of the nearly-Gaussian beam (inset of Fig. 1) due to thermal effects could be observed. The stability of the amplified pulse energy was measured with a photodiode and indicated fluctuations on the order of 0.3% rms within a time-span of 300 seconds (Fig. 3). There are two main reasons for this high stability. First, the QCW pump pulse duration was chosen to be significantly longer than the upper state lifetime of Nd:YVO_4 ($\leq$100 μs [14]), which completely saturated the inverted region in the amplifier crystal and therefore made the system less prone to fluctuations of the QCW diode output power. Second, gain depletion damped the amplified pulse energy fluctuations originating from amplitude noise of the master oscillator (0.6% rms within 300 seconds). The oscilloscope trace depicted in Fig. 4 illustrates the effect of the gain depletion on the amplification of a second, slightly delayed pulse of equal seeding energy. The inset shows the amplified pulse-to-pulse contrast of 400:1, which, due to saturation effects, is slightly lower than the initial >1000:1 contrast after the pulse-picking.

3.2. Double-pulse sequences

In addition to the described single-pulse operation, the system can also be used to produce adjustable pulse sequences as described in [11], but now producing equal pulses at the mJ-level as shown in Fig. 5. Because of the high level of gain depletion, the seed energy of the first pulse was adjusted to be $\leq 20\%$ of the seeding energy of the second pulse.

In order to test the compatibility, the double-pulse output of the presented pump front-end was further amplified in our previously used flashlamp-pumped post-amplifier, consisting of two 12 mm diameter Nd:YAG rods in a double-pass configuration. By further lowering the seeding energy of the first pulse in order to also pre-compensate the gain depletion in the post-amplifier, two equal 1064 nm pulses of each 140 mJ pulse energy were obtained. The

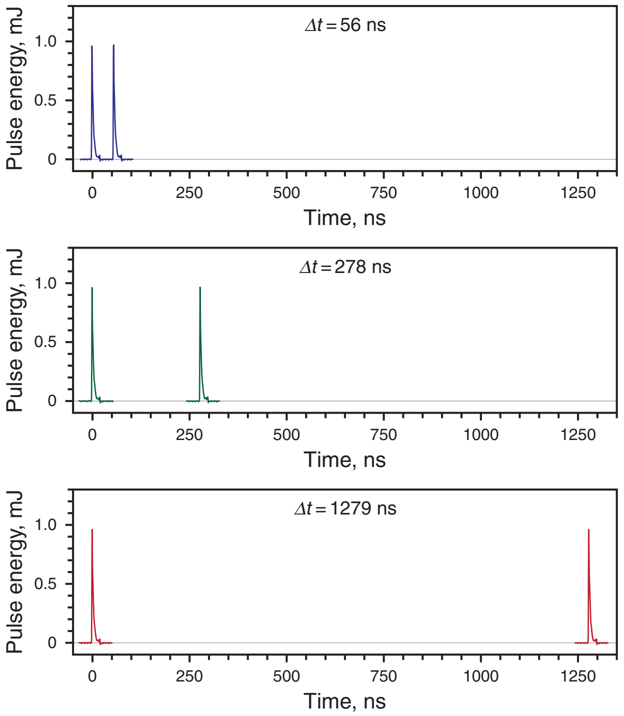

Figure 5 (online color at www.lasphys.com) Time traces of amplified pulse pairs after the bounce amplifier for different temporal spacings (equal to multiples of the cavity round-trip time of the master oscillator)

flashlamp-pumped post-amplifier currently limits the repetition rate to ≤30 Hz, but this part is intended to be replaced by diode-pumped modules in order to enable an overall repetition rate of 300 Hz.

4. Conclusion

We presented a pump front-end system based on two ultrahigh gain grazing-incidence Nd:YVO_4 amplifier slabs, delivering highly stable (0.3% rms) picosecond pulses of more than 1.8 mJ at a repetition rate of 300 Hz. In addition, with the help of fast programmable modulators, adjustable mJ-pulses-sequences were produced, and by subsequent amplification two equal 1064 nm pulses of more than 140 mJ could be obtained. The extended temporal delay between these pulse pairs will potentially enable kHz-level XUV frequency comb spectroscopy based on the two-pulse approach as demonstrated in [4].

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